

THE ULTRAVIOLET SPECTRUM OF THE CRAB NEBULA

Hugh M. Johnson
Lockheed Missiles and Space Company
Palo Alto, California

I. INTRODUCTION

Before the OAO-2 no observations of the Crab Nebula were available between 3210 Å from ground-based photoelectric observations (O'Dell 1962) and one-quarter keV in the soft X-ray region (Fritz *et al.* 1971; Coleman *et al.* 1971). This paper reports new observations made under the OAO-2/NASA guest investigator program with the WEP "stellar" photometers described by Code *et al.* (1970). The 10'-diameter focal-plane diaphragm is ample to accept the 4' × 6' image of the Crab. Figure 1 shows the data of the Crab as processed by the principal investigators of WEP. It gives the logarithm of the integrated relative intensity per wavelength interval, corrected for sky background, and the rms error, from 11 passbands in the range 4250-1380 Å. No correction has been made for polarization of the light. The data are converted to logarithm of the flux density per frequency interval, F_ν , and plotted on scales of $\log \nu$ (Hz) and of reciprocal microns (μ^{-1}) in Figure 2, with two adjustments. First, the OAO-2 data are normalized to O'Dell's (1962) data in the range 3210-4280 Å, and all of the data including O'Dell's are corrected for interstellar extinction.

II. INTERSTELLAR EXTINCTION AND THE CRAB SPECTRUM

The total extinction at wavelength λ is

$$A_V + E(\lambda-V) = A_V + E(\lambda-V)/E(B-V) \times A_V/R \quad (1)$$

where A_V is total extinction in the V passband, $R = A_V/E(B-V)$ is its ratio to color excess $E(B-V)$, and $E(\lambda-V)/E(B-V)$ is the ratio of the color excesses at λ and at the B passband. Then $0.4[A_V + E(\lambda-V)]$ is the correction for extinction to the loga-

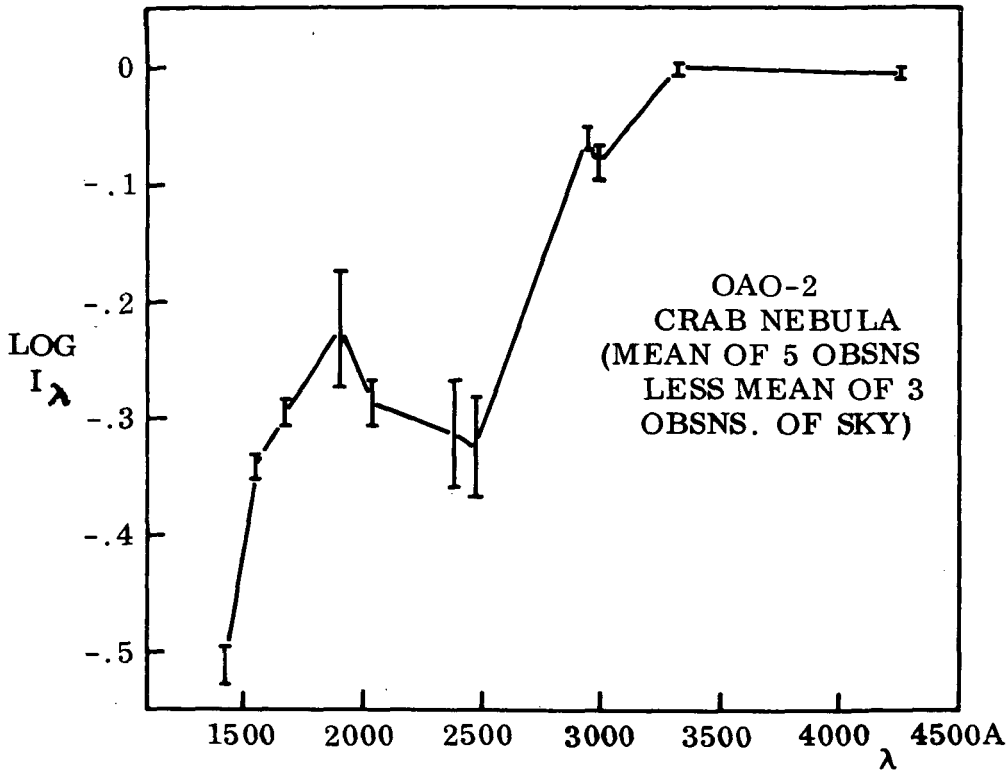


Figure 1.—OAO-2/WEP photometer observations of the Crab Nebula.

rithm of observed intensity. We proceed first with estimates of A_V and R made independently of the OAO-2, and with the OAO-2 observations of $E(\lambda-V)/E(B-V)$ made independently of the Crab by Bless and Savage (1972). Minkowski (1968) estimates $A_V = 1.9$ mag for the Crab, and Johnson (1968) estimates $R = 6$ approximately in the direction of the Crab. These values are used in equation (1) for Figure 2. Unfortunately for making corrections to the observed spectrum of the Crab, $E(\lambda-V)/E(B-V)$ is not uniform in the Galaxy and we do not know the preferred function in the line of sight to the Crab. The "average" curve and the " θ Ori" curve of $E(\lambda-V)/E(B-V)$ are both used in Figure 2. Table 1 lists some of the relevant data. Although O'Dell's (1962) optical data are only slightly differently corrected according to the two extinction curves, the OAO-2 data fall into two quite distinct branches according to choice of $E(\lambda-V)/E(B-V)$, keeping $A_V = 1.9$ mag and $R = 6$. Both branches are steeper than the spectrum $F_\nu \propto \nu^{-1.0 \pm 0.1}$ which Peterson and Jacobson (1970) have found to hold over the range of 1 - 500 keV in the Crab. The extrapolation of this X-ray spectrum is shown for comparison in Figure 2. The uncertainty in

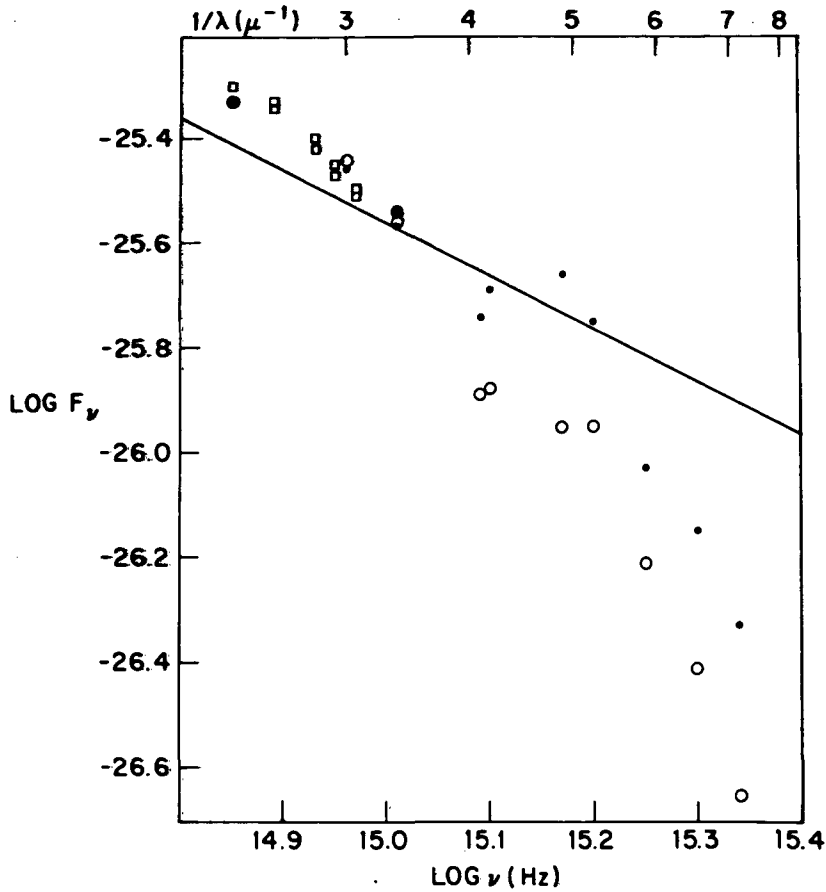


Figure 2.—The solid and open circles are the data of Figure 1 in transformed coordinates and corrected for extinction according to Bless and Savage's (1972) "average" and "θ Ori" curves, respectively. They are normalized to O'Dell's (1962) data (squares). The straight line is an extrapolation of Peterson and Jacobson's (1970) X-ray spectrum of the Crab Nebula, starting at the frequency of 1 keV = 2.42×10^{17} Hz and the flux density of $17.2 \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ keV}^{-1} = 1.14 \times 10^{-28} \text{ W m}^{-2} \text{ Hz}^{-1}$, with the power-law spectral index = -1.

$\log F_\nu$ corresponding to the uncertainty of ± 0.1 in the exponent on ν is about ± 0.34 at $\log \nu = 14.97$ since the latter differs from $\log \nu$ (10 keV) by 3.4. It is the observed and corrected slope $dF_\nu/d\nu$ which is significant in a comparison with the extrapolated X-ray spectrum rather than the level of observed and corrected F_ν . The "average" branch also shows an apparent emission hump around $1/\lambda = 4.6 \mu^{-1}$, and the "θ Ori"

Table 1. Data of the Crab Nebula for Figures 1 and 2.
 F_V Normalized to O'Dell's (1962) Optical Data.

WEP Photometer Filter	Effective $\log v$	Relative $\log I_\lambda$	$\log I_V$	Average extinction $\frac{E(\lambda-V)}{E(B-V)}$		θ Ori extinction $\frac{E(\lambda-V)}{E(B-V)}$	
				$\log F_V$ ($\text{Wm}^{-2}\text{Hz}^{-1}$)	$\log F_V$ ($\text{Wm}^{-2}\text{Hz}^{-1}$)	$\log F_V$ ($\text{Wm}^{-2}\text{Hz}^{-1}$)	$\log F_V$ ($\text{Wm}^{-2}\text{Hz}^{-1}$)
S1F3	14.85	0.00	+0.22	1.14	-25.33	1.14	-25.33
1	14.96	0.00	0.00	1.85	-25.46	1.96	-25.44
4	15.01	-0.08	-0.17	2.31	-25.57	2.34	-25.56
S2F2	15.01	-0.06	-0.16	2.45	-25.54	2.45	-25.54
5	15.10	-0.31	-0.60	4.75	-25.69	3.23	-25.88
1	15.17	-0.29	-0.71	5.85	-25.66	3.54	-25.95
S3F2	15.09	-0.33	-0.59	4.24	-25.74	3.11	-25.89
1	15.20	-0.22	-0.69	4.96	-25.75	3.36	-25.95
5	15.25	-0.30	-0.89	4.32	-26.03	2.89	-26.21
S4F1	15.30	-0.34	-1.03	4.48	-26.15	2.47	-26.41
3	15.34	-0.51	-1.27	4.97	-26.33	2.44	-26.65

branch is inflected in the same vicinity. The emission hump may simply reflect the shape of the extinction curves. All of the curves plotted by Bless and Savage (1972) show an absorption maximum near $1/\lambda = 4.6\mu^{-1}$, but the curve for θ Ori shows it least markedly. If average extinction were overestimated, a false emission hump would appear on a smooth spectrum, while θ Ori-type extinction might not show it.

It may appear simple to select a curve of $E(\lambda-V)/E(B-V)$ and vary the parameters A_V and R until the corrected spectrum is smooth and agrees in slope with the extrapolated X-ray spectrum; it is not known, incidentally, whether R is independent of the shape of $E(\lambda-V)/E(B-V)$. The observed flux densities of the Crab at, say, the extremities $\log \nu = 14.85$ and $\log \nu = 15.34$ differ logarithmically by 1.49, while the extrapolation of the X-ray flux density changes logarithmically by 0.49 in the same interval. Therefore we want to correct the observed spectrum by about 1.00 in $\log F(\log \nu = 14.85) - \log F(\log \nu = 15.34)$ in order to match the slope of the X-ray spectrum. When the values of the average curve of $E(\lambda-V)/E(B-V)$ at these frequencies are used, we find $E(B-V) = 0.65$ and $A_V = 2.0$ mag ($R = 3$) or $A_V = 3.9$ mag ($R = 6$). Similarly for the θ Ori curve of $E(\lambda-V)/E(B-V)$, $E(B-V) = 1.92$ and $A_V = 5.8$ mag ($R = 3$) or $A_V = 11.5$ mag ($R = 6$). Thus it appears that the observed spectrum would be corrected very nearly to the slope of the X-ray spectrum by using Minkowski's (1968) $A_V = 1.9$ mag, but with $R = 3$ rather than $R = 6$ as in Figure 2. Any use of the θ Ori curve of $E(\lambda-V)/E(B-V)$ appears to require excessive visual extinction in order to match the slope of the X-ray spectrum. However, if the average extinction curve is indeed used with $A_V = 1.9$ mag and $R = 3$, the emission hump becomes even stronger than it appears in Figure 2, and the data of the three highest frequencies break into a steep slope. The conclusion is that the OAO-2 data of the Crab cannot simultaneously match the slope of the X-ray spectrum and remain smooth. It is, of course, possible that a recalibration of the WEP photometer efficiencies would alter the conclusion. It is unlikely that a least-squares solution of all of the observed data of the Crab, rather than the present use of the data of the two extreme frequencies, would alter the conclusion.

III. QUESTIONS ABOUT THE CRAB FILAMENTARY NEBULA

There is, of course, no reason to match the observations with the simple extrapolation of the X-ray spectrum of the Crab, except the simplicity of it. Also, the pulsar spectrum or the filamentary spectrum might rise to be a significant contribution in the ultraviolet. The following nebular emissions are predicted (Osterbrock 1963) in the filamentary spec-

trum near the $1/\lambda = 4.6 \mu^{-1}$ peak: recaptures by He^+ (2^3S series limit at 2600 Å), recaptures by He^{2+} ($n = 3$ series limit at 2051 Å), and the 2-photon continuum with a maximum at 2431 Å. The $n = 3$ series limit of He^{2+} is interesting because the first line of the series, He II 4686, is unaccountably strong in the filament spectrum according to Davidson and Tucker (1970). There are no good candidate line emissions, and one such line would not explain the $1/\lambda = 4.6 \mu^{-1}$ peak which appears in four separate passbands. We may only conclude, in the absence of a quantitative evaluation, that the filamentary continua may be significantly necessary because of the rather positive conclusion against a featureless continuum in the previous section.

Woltjer (1958) assumed an ultraviolet continuum of the amorphous component to explain the observed excitation conditions in the filaments of the Crab in terms of photoionization and heating. Davidson and Tucker (1970) have specified four alternative models of the high-frequency continuum to investigate these effects on the filaments. The OAO-2 data do not make obvious a choice of any one model, because the power-law spectral index in the observed range of frequencies can be, according to the different extinction curves, either -1.2 or -2 as in the models. This conclusion ignores the $1/\lambda = 4.6 \mu^{-1}$ hump and the probable curvature of any of the corrected spectra. The theoretical models of Davidson and Tucker do not, in turn, tell how to correct the observed Crab spectrum for extinction because they are ambiguously capable of explaining most of the line spectrum of the Crab filaments, except the high intensity of He II 4686.

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